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Abstract

In 2005, a fuel cell bus manufactured by the French company IRISBUS will operate in the streets of Paris.
Under the French automotive regulation, IRISBUS is allowed to run its fuel cell prototype, provided that it guarantees its safe operation. This task requires a risk analysis to be carried out. INERIS has been chosen to drive this study. This paper reviews the risk assessment methodology and results. It highlights that maintenance and use are the most critical stages because of potential aggressions on the hydrogen system. It also indicates that the greater hazard potential lies in high pressure hydrogen storage and distribution. As such, it appears that more information is required on high pressure tank behaviour faced with different thermal and mechanical aggressions. Beyond, thermal fuse reliability has to be known. However, this bus features design principles and safety barriers that bring the risk down to an acceptable level.

Introduction

IRISBUS is born from the joint venture between RENAULT and IVECO BUS. It launched a project named CITYCELL which consists in running different fuel cell buses in 3 European cities: Paris, Turin and Madrid.
The present paper concerns the French demonstration bus that will be operated by the Parisian transport company, RATP[1]. So as to run the bus in the French capital and carry public passengers, IRISBUS shall get due authorisation from the French Ministry of Transport.

Since there is no specific regulation for fuel cell vehicles approval neither under the French automotive regulation nor at a European level, IRISBUS was asked by decision makers to demonstrate the safe operation of the bus for prototype approval.

INERIS has been tasked by IRISBUS to perform the bus preliminary risk analysis. This analysis targets the safe use of hydrogen.
This paper will review methodology and the main conclusions in terms of risks and mitigation techniques for the different running stages.

[1] Régie Autonome des Transports Parisiens

1. Technical specifications

The proposed vehicle is a twelve meter articulated bus (see figure 1 below). It results from the combination of a trolley bus (external electrical power supply) and a fuel cell system. The power system is an hybridation between a 75 kW PEMFC and batteries. Batteries are a mean to recover braking and deceleration energy. They also supply additive power for peak demand.

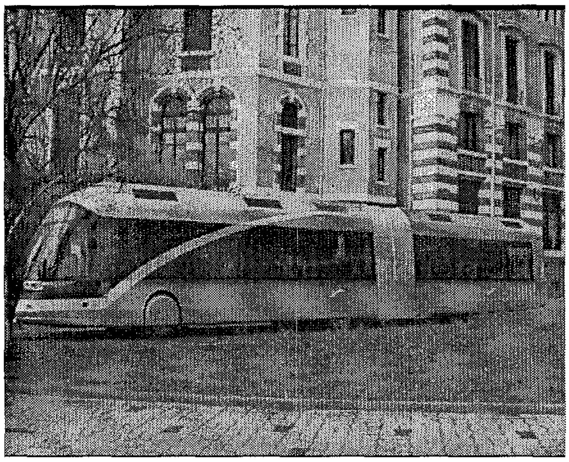

Figure 1: Trolley bus – The Civis Cristalis

The bus is expected to have an autonomy of 200 km. Seven 150 litres pressurised composite tanks are used to store hydrogen. Tanks are made of an aluminium liner wired with carbon fibre impregnated by an epoxy resin. They have a service pressure of **350 bar**. The system allows to store about 20 kg of hydrogen. All together, it weights about 580 kg.
Each tank is equipped with :

- a manual valve for hydrogen purging (maintenance),
- a thermal fuse to discharge hydrogen in case of fire,
- a safety valve.

The stack will be located at the rear of the bus. Tanks as well as high pressure lines will be mounted on the roof.
Along with the bus, a urban hydrogen filling station will be experimented.

2. Regulatory aspects

Currently, vehicle approval refers to European directive (Council Directive 70/156/EEC on the approximation of the laws of the Member States relating to the type-approval of motor vehicles and their trailers).
This European directive does not cover vehicles running on hydrogen.

Meanwhile, under the same European directive, there are two ways for a manufacturer to run its prototype on the street:

- The vehicle manufacturer can refer to its own national authorities to gain a prototype approval. This prototype approval is valid as long as the number of vehicles is kept below 500 units per year. This national approval does not entitle to exportation unless the European exporting country agrees with this approval. In this case, the vehicle runs with a "W" type registration number. As long as the bus does not carry passengers, responsibility falls on the manufacturer. In other cases, public authorities are responsible.

- For larger production and for innovative technologies, any national authority belonging to the European Economic Community can submit a technical file to the European Commission. If the evaluation output is positive, the approved vehicle will be allowed to run freely within the 15 member states for a given period of time.

The first option is tailor-made for prototypes such as the present bus. Therefore, this option was chosen. On the basis of a risk analysis, Ministry of Transports is expected to deliver due authorisation.

Both options are interesting as long as prototypes or innovative vehicles are concerned. In the longer term, the current legal context will slow down hydrogen vehicles commercialisation.

The European project EIHP[2] aims at proposing an harmonised procedure for hydrogen vehicles approval. EIHP proposals for liquid and pressurised hydrogen storage onboard vehicles have been forwarded to an ad-hoc GRPE group in Geneva. International regulations proposals are expected to evolve from this group.

3. Risk analysis : methodology

Proper risk analysis requires transversal skills and knowledge to be mixed. For example, this project working group gathered people from conception (stack, bus and storage), maintenance, as well as end-users along with safety experts.
Unfortunately, none of the participants was representing rescue services.

The graph below (figure 2) shows the different steps involved in the risk analysis.

[2] European Integrated Hydrogen Project

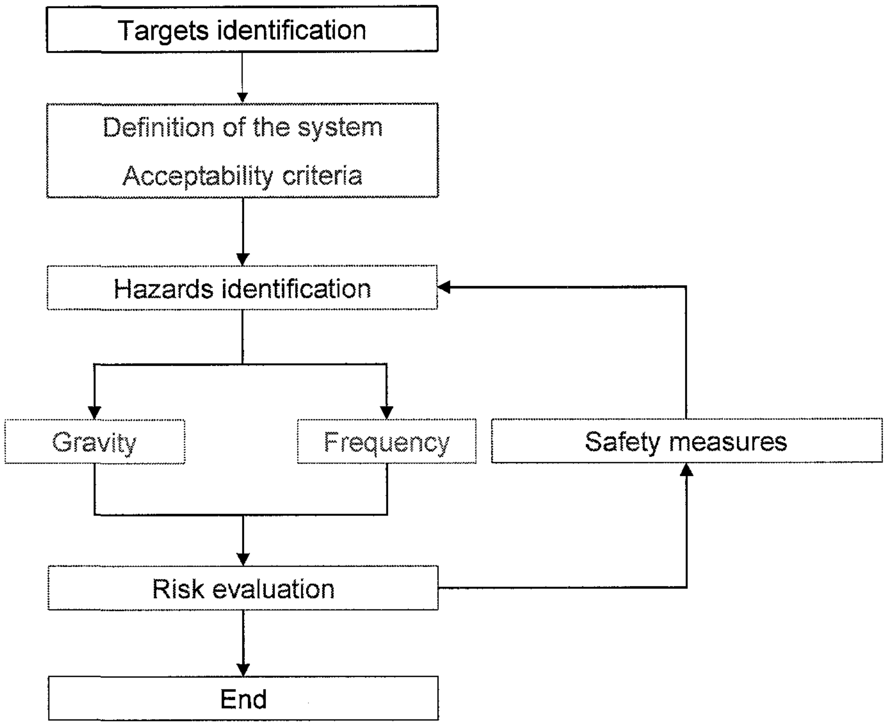

Figure 2: Logical steps in risk analysis

A risk analysis requires targets to be identified. In a second time, the system has to be thoroughly described. Hazards inherent to the system as well as those coming from its environment shall be identified. The use of past experience (conventional and CNG buses) shall help in this task. Unwanted events that generate these hazards are referenced in a table similar to the one shown below. This table also mentions unwanted events likelihood and severity.

Function : *hydrogen storage*							**Date :**		
Product or equipment : *tanks*									
N°	**Unwanted event**	**Cause**	**Consequences**	**G**	**Existing safety measures**	**F**	**Added safety measures**	**G**	**F**

Table 1: Risk analysis table

Likelihood and severity criteria are set prior to carry the risk analysis (see tables 2 and 3). Their combination sets a criticity which is then compared with a risk acceptance level (see table 3).

Gravity	Effects on people
G4	Lethality or strong permanent disability
G3	Injuries with low permanent disability
G2	Injuries with temporary disability
G1	Minor injury

Table 2: Gravity quotation

Frequency	Event	Definitions	Corresponding safety barriers
F4	Likely (1per year)	Is likely to happen bus operation	Procedures
F3	Rare (1per 10 years)	Has happened on other similar systems	Procedures & automatic control
F2	extremely rare (1per 100 to 1000 years)	Conceivable, has happened, whatever the system	Same as above + additional barrier
F1	Unlikely	Speculative	Same as above + additional barrier

Table 3: Frequency quotation

Gravity 4	4 1	4 2	4 3	4 4
Gravity 3	3 1	3 2	3 3	3 4
Gravity 2	2 1	2 2	2 3	2 4
Gravity 1	1 1	1 2	1 3	1 4
	Frequency 1	**Frequency 2**	**Frequency 3**	**Frequency 4**

Table 4: Criticity matrix

Safety measures drive the system back to an acceptable risk level (white area in table 4). Both number and type (procedures or technical measures) of barriers are related to the estimated criticity.

Safety measures implementation follows usual principles that consist in :

1. eliminating the hazard (conception choices),
2. reducing the hazard (conception choices and safety measures),
3. mitigating its effects (safety measures),
4. and finally removing or moving potential targets away from the hazard.

Safety barriers are expected to comply with specifications such as :

- fail safe conception,
- ability to be tested and maintained,
- ability to withstand expected aggressions,
- ability to work in the case it suffers a default.

Finally, their conception shall rely on a proven technology.

4. Results and discussion

All running conditions have been studied. That is to say :

- the hydrogen filling stage,
- the bus maintenance and cleaning,
- the use of the bus with passengers in a urban environment,
- and finally the bus parking.

Tunnel crossing has not been looked at. The working group suggested that experience should be gained before considering tunnel crossing.
The filling station itself is also out of the frame of this study.

To ease the study, the bus has been split into its main functions:

- hydrogen storage and supply to the stack,
- hydrogen conversion (air supply, electrochemical conversion, heat dissipation, outflow management, ...),
- electrical architecture,
- vehicle.

According to this, noticeable unwanted events are listed in table 5 prior to be further discussed.

	Hydrogen filling stage	Bus maintenance and cleaning	Use of the bus with passengers in a urban environment	Bus parking
Hydrogen storage and supply to the stack	– Excessive storage pressure – Hydrogen leakage – Hydrogen release (PRD) – Burst of tank	– Indoor high pressure hydrogen leakage – Indoor hydrogen release – Burst of tank	– Outdoor high pressure hydrogen leakage – Outdoor hydrogen release – Burst of tank	– Burst of tanks – High pressure leakage
Hydrogen conversion		– Low pressure hydrogen leakage	– Low pressure hydrogen leakage within the stack compartment	– Low pressure leakage
Electrical architecture	– Ignition sources	– Electrical shock	– Electrical shock to passengers, people and rescue services	– Electrical shock to workers or trespassers
Vehicle	– Bus in fire	– Bus in fire – Accident with other buses	– Hydrogen leakage within the passenger compartment – Bus in fire – Road accident	– Accident with other buses – Bus in fire

Table 5: List of unwanted events

The hydrogen filling stage

Hydrogen leakage is quite a likely event as large quantities of high pressure hydrogen are transferred from the station to the bus. Besides, many situations can cause a leakage (improper plugging, open gates, tearing of dispenser lines, ...). Hazard associated to this situation is connected to the leaking flow, its duration, as well as to hydrogen potential to accumulate. Knowing the prone ability of hydrogen air mixture to be ignited, it is taken for granted that ignition will take place. Indeed, industrial experience shows that adequate hydrogen air mixture ignites most of the time.

Hydrogen release can be caused by a normal or abnormal opening of PRDs or safety thermal fuses. These releases are collected in order to be vented in a safe location.

Bus fire can be the consequence of ignited hydrogen leakage, electrical default, maintenance work, ... Fire is critical since it can eventually cause the burst of tanks. Burst of one tank can induce the burst of the other ones because of flying debris. Tank burst can also release sufficient energy to punch the passenger carrier compartment.

For safety reasons, filling takes place outside in a restricted access dedicated filling station. Ignition sources are controlled through the use of adequate electrical equipment, prohibition of work, switching of bus power sources, ... Hydrogen detection, pressure drop detection, accidental disconnection, ... cause filling to stop in emergency. Finally, hydrogen flow is limited and lines are fitted with check valves. Whenever, an explosion occurs the filling station is located away from other industrial equipment and dwellings.

Maintenance and cleaning

Maintenance is one of the most critical stage. Indeed, it can imply to act directly on the hydrogen distribution circuit in confined conditions. Confinement prevents hydrogen dispersion and dilution. It is therefore liable to significantly increase explosion hazards. Mechanical or natural ventilation prevents hydrogen from accumulating. However, it has no effect whatsoever on the dispersion plume, which is linked to the leaking diameter and pressure. Moreover, in a maintenance context, fire is a likely event (use of open flames to facilitate mechanical dismantling).

Leakage on the low pressure circuit is not that critical because of quantities of hydrogen and relative explosive volume that can be formed. This remark is valid, as long as the low pressure circuit is isolated from the high pressure one. Local confinement also has to be avoided.

Tanks rupture can be feared in case of inappropriate maintenance (drilling, open flames, ...). Drop of heavy loads carried above the tanks could also punch them.
Finally, attention should be paid when maintenance concerns safety equipment. Their working conditions can be altered.
To mitigate explosion hazards, it has been recommended whenever possible to limit tank pressure before to enter maintenance workshop. A list of critical maintenance work requiring tank to be emptied has to be drawn. A bay will be dedicated to hydrogen bus maintenance. This bay will have special features: control of ignition sources, hydrogen sensors, and ventilation eventually.
High pressure lines are shielded against mechanical aggressions.

The use of the bus with passengers in a urban environment

In this situation, targets and hazards sources are numerous. Road collisions is one of them. Experience shows that the 4 000 Parisian buses suffer annually about 10 000 accidents. Most of these accidents concern the front right or left hand side of the bus. The low part of the chassis is usually concerned. In a urban situation, many other aggressions have been thought of: drop of objects from balconies, gun shot, falling trees, vandalism, ...
CNG buses are to some extend comparable to the hydrogen ones. Experience with the 53 buses operated in Paris for the last 3 years indicates that natural gas sensors went of 20 times. Too low triggering level and exhausted gases were responsible for all of these detections. Once, a thermal fuse opened untimely because of friction between the fuse and the tank cover.

Whereas in the previous stages emergency means were more or less ready for action, in a urban context, it might take time for rescue services to intervene.
Besides, it turns to be more difficult to set a safety perimeter in case of an accident. On the other hand, outdoor conditions enhanced hydrogen dispersion even though high buildings may refrain secure plume dilution.

Massive leakage can generate an explosive atmosphere as well as jet flames. Thermal fuses default leads to a leak that can not be stopped unless the tank is empty. Normal PEMFC purging does not cause any hazardous situation knowing the quantity of hydrogen involved.

Explosive atmosphere within the passengers carrier compartment has also been identified. This compartment is isolated from hydrogen equipment. High pressure lines are mounted on the roof to facilitate hydrogen dispersion. Finally, on a precautionary principle, a hydrogen sensor has been installed within the passenger compartment.

In case of a fire, the driver is expected to tackle the flames with a 6 kg powder extinguisher. He also invites passengers to evacuate. Evacuation takes no more than 5 minutes. Knowing the possibility for tanks to burst, a safety zone will have to be enforced. Time required for passengers and public to evacuate the zone has to be assessed. Possible burst shall not take place before this time.

Accidents can expose live parts. Circuit breaker and isolation means are used to prevent electrical shocks to passengers or rescue services. Moreover, high voltage parts will be tagged. Rescue services will be informed about specific explosive and electrical risks induced by this new technology.

Flow limiter and small diameter piping prevent large explosive atmosphere volumes. Length of high pressure lines is kept to a minimum. R110 rules will be followed. Leakage or catastrophic rupture would induce pressure drop. Drop in pressure detection causes feeding gates to shut off. Regarding the stack itself, electrical equipment are physically isolated from hydrogen equipment. All these equipment are ventilated.
Finally, use of combustible material is controlled in order to prevent fire from rapid propagation.

The bus parking

On a parking stand, internally or externally triggered fire is possible. As said before, fire can ultimately be responsible for the burst of tanks. This risk has to be taken into account, while

getting the fire under control. The hydrogen bus motion shall not be bounded to other buses position, in order to be able to move it freely if it is not on fire. Outdoor parking mitigates potential explosive atmosphere volumes and effects.
Hydrogen gates shall be in a closed position and electrical parts shall be discharged as the bus is parked.

The table below summarises most of the selected safety barriers for all stages.

	Hydrogen filling stage	Bus maintenance and cleaning	Use of the bus with passengers in a urban environment	Bus parking
Hydrogen storage and supply to the stack	– Outdoor filling station – Dedicated filling dispensers – Check valve on tanks – Limitation of equipment on H_2 lines – Welding check – Safety filling pipe – Training – Prohibition of any maintenance work during filling – Restricted access to the filling station – Control of ignition sources – Filling is not possible if the bus is running – H_2 detection, pressure drop, disconnection, induced emergency stop of filling – Pressure control – Flow limiter – Safety distances with other equipment	– When possible limitation of tank pressure – Mechanical protection of high pressure lines – Training – Tests of high pressure circuit after maintenance – Dedicated bay for hydrogen bus maintenance – Control of ignition sources – Emptying of tanks for heavy or timely maintenance – Hydrogen venting is collected and discharged in a safe location	– Implementation of R110 rules – Length limitation of high pressure lines – High pressure lines are located on the roof; they are also protected – Leaking flow does not exceed 4 times stack H_2 consumption – Pipe diameter is minimum – Pressure drop detection – Possibility to isolate tanks	– Gates ensure isolation of tanks from high pressure circuit – Outdoor parking
Hydrogen conversion		– Forced ventilation – Detection	– H_2 detection	– Ventilation of stack compartment before start-up
Electrical architecture	– Internal bus power sources are switched off (H_2 bus sensors are kept in function)	– Tag and lock procedure – Discharge of electric capacities	– Electrical isolation between passenger compartment and electrical system – Floating mass – Circuit breaker	– Discharge of electric capacities – Internal bus power sources are switched off
Vehicle	– Fire fighting measures and equipment – Evacuation procedures	– Fume detection – Fire fighting measures and equipment – Critical safety equipment have been identified for a specific maintenance procedure	– Tag of high voltage equipment – H_2 detection in passenger compartment – Isolation between H_2 circuit and passenger compartment – Tanks and high pressure lines on the roof – Use of non combustible materials	– Freedom of movement – Fire fighting measures and equipment – Evacuation procedures

Table 6: List of proposed safety barriers

Hydrogen storage and high pressure lines are the most hazardous part of the bus. Bursting and leaking potentiality has to be better understood and quantified for all types of aggressions. The following paragraphs discuss these events.

High pressure hydrogen storage : how safe is it safe ?

Jet flames, explosive atmospheres or burst of tank can be induced namely by:

- local (jet flames) or global thermal aggressions (bus on fire);
- mechanical aggressions (road accidents, falling objects, flying debris, gun shot, …).

The graph below illustrates some of the causes leading to unwanted effects.

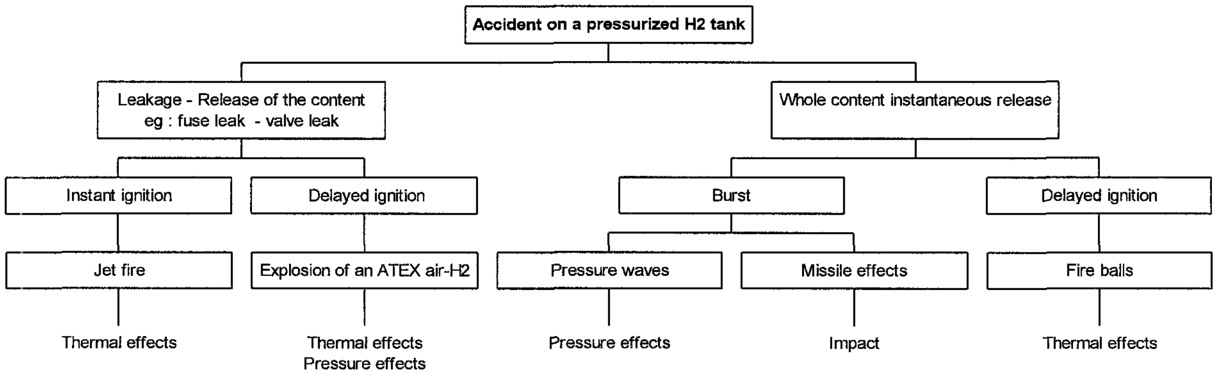

Figure 3: Tank accidental situations

❖ Thermal aggressions

Thermal aggressions can ever be local (jet flame from an opened thermal fuse) or global (bus on fire). Whatever extensive the aggression is, safety measures shall be taken to prevent tanks from bursting.

For global aggressions, the following questions have to be answered:

- What is the likelihood for a thermal fuse to remain closed ?
- What is the influence of the fuse location in its ability to operate properly ?
- Is there any critical thermal flux for which the tank can burst before it is depressurised ?
- In the event of thermal fuse failure, how long will it take for the tank to burst ?

Untimely fuse opening likelihood is also to be quantified. Combination of fuse reliability and sensibility shall indicate how many fuses are to be fitted to a pressurised tank.

Some tests[3] have shown that bursting can be induced by local aggressions. These tests indicate once more that number and location of fuses should be adequately set. It also underlines that tank structure must withstand the local aggression during the time required to get its pressure down.

Tank bursting is not an acceptable event, unless either its likelihood is speculative or people have sufficient delay to get themselves in a safe location.

[3] J. CHAINEAUX, *« Security of highly pressurised tanks equipping GH_2 fuel road vehicles »*, Contract n° 13461-97-11 F1ED ISP F, november 2000

❖ Mechanical aggressions

The safety study has shown that tanks can be submitted to various mechanical aggressions: punch, shock, impact, crash, … It is worth knowing tank behaviour to these aggressions. In this particular case, tanks are located on the roof, that is the less vulnerable part of the bus. Moreover, there are tightly linked to the chassis in accordance with R110[4] rule.
Regarding collision head on (collision with tunnels), tanks are protected by the chassis. A top cover also protects them from sun light and minor mechanical aggressions.

Conclusion

This safety analysis browses all situations of bus operation. It highlighted that maintenance and use are the most critical stages because of potential aggressions on the hydrogen system. It also highlighted that the greater hazard potential lies in high pressure hydrogen storage and distribution.

As such, it appears that more information is required on high pressure tank behaviour faced with different thermal and mechanical aggressions. Beyond, thermal fuse reliability has to be known.

However, this bus features design principles and safety barriers. They bring the risk down to an acceptable level as long as high pressure tank safety equipment work as expected.

This safety analysis is the preliminary link of a safety chain that includes calculations on potential explosive atmosphere volumes in case of line rupture or thermal fuse opening, overpressures related to tank burst and related safety distances,… It also includes more detailed AMDEC / HAZOP studies on the stack and the storage itself.

All together, it consists of the initial step of a safety program that includes:

- the check of critical equipment prior to be mounted on the bus,
- the set up of a database to collect defaults and incidents in order to improve whenever required the overall safety level,
- the definition of specific maintenance procedures,
- and finally the training of drivers, mechanics and rescue services.

This demonstration project should bring sufficient experience on bus operability, safety and related public perception. Further use in tunnel for instance will then be considered.

[4] R 110 : Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions